The Optimal Timing of Greenhouse Gas Emission Abatement, Individual Rationality and Intergenerational Equity

Richard S.J. Tol*

NOTA DI LAVORO 3.98

JANUARY 1998

ENV - Environmental Economics

*Institute for Environmental Studies,
Vrije Universiteit Amsterdam

This paper was presented at the Conference on "International Environmental Agreements on Climate Change", Venice, May 6-7, 1997, organised by Fondazione Eni Enrico Mattei and the Stanford Energy Modeling Forum with the sponsorship of IPCC and under the auspices of EFIEA.

Address for correspondence:

Richard S. J. Tol
Institute for Environmental Studies
Vrije Universiteit
De Boelelaan 1115
1081 HV Amsterdam
The Netherlands
Phone: +31+20+4449555
Fax: +31+20+4449553
E-mail: richard.tol@ivm.vu.nl

SUMMARY

This paper explores the relationship between rationality and equity in an intergenerational context of greenhouse gas emission reduction. It is shown that the least-cost trajectory to a constraint on cumulative emissions implies an upward-sloping emission reduction effort, in most cases, whether technological development is exogenous or endogenous (either investments in research, development and demonstration or learning-by-doing). The least-cost trajectory, however, also implies in most cases that generations in the further future face higher relative costs than do generations in the nearer future. Cost-effectiveness thus may well violate intergenerational equity and rationality of future decision makers. More equitable solutions would lead to a relative shift of abatement effort to the near future, although emission reduction would still be increasing over time. In all cases, technological development in the earlier decades is very important.

Keywords: Climate change, Timing of emission abatement, Cost-effectiveness, Rationality, Equity

JEL: Q25, Q40

NON TECHNICAL SUMMARY

A least-cost strategy towards stabilising the atmospheric concentrations of greenhouse gas emissions apparently implies that emissions do not have to be substantially reduced in the short term, but that drastic emission control is better postponed to a more remote future. The first half of this paper shows that this conclusion is qualitatively robust. Under a wide variety of assumptions, the cost-effective emission reduction trajectory starts low and slopes upward. There is, however, considerable room for debate on how low 'low' should be (although it should be greater than zero) and on how steep the upward slope should be.

The second half of the paper draws attention to the fact that cost-effectiveness reflects the interests of the current generation. Deferring abatement action implies shifting its costs to the future. This may be inequitable. It is inconsistent with the rationality of later generations, who will have incentives to weaken the stabilisation target.

A solution may be a "non-envy" emission path, in which each generation bears the same relative cost of emission abatement. This path implies higher near-term reductions compared to the cost-effective trajectory. The emission limitation profile is still upward sloping, because of technological progress.

THE OPTIMAL TIMING OF GREENHOUSE GAS EMISSION ABATEMENT, INDIVIDUAL RATIONALITY AND INTERGENERATIONAL EQUITY

Richard S.J. Tol
Institute for Environmental Studies, Vrije Universiteit Amsterdam

28 July 1997

Abstract
This paper explores the relationship between rationality and equity in an intergenerational context of greenhouse gas emission reduction. It is shown that the least-cost trajectory to a constraint on cumulative emissions implies an upward-sloping emission reduction effort, in most cases, whether technological development is exogenous or endogenous (either investments in research, development and demonstration or learning-by-doing). The least-cost trajectory, however, also implies in most cases that generations in the further future face higher relative costs than do generations in the nearer future. Cost-effectiveness thus may well violate intergenerational equity and rationality of future decision makers. More equitable solutions would lead to a relative shift of abatement effort to the near future, although emission reduction would still be increasing over time. In all cases, technological development in the earlier decades is very important.

Keywords
Climate change, timing of emission abatement, cost-effectiveness, rationality, equity

JEL Classification
Q25, Q40

1. Introduction

A paper published by Wigley, Richels and Edmonds in *Nature* in 1995 aroused considerable discussion. Wigley *et al.* (1995; WRE, henceforth) conclude that most cost-effective trajectories towards stabilization of greenhouse gas concentrations in the atmosphere have a typical shape: a cost-effective trajectory closely follows the business as usual path in earlier decades, to sharply bend away from it in later decades, deeply cutting emissions from baseline in later years. Later studies confirm this (Edmonds *et al.*, 1997; Manne and Richels, 1997a,b; Peck and Teisberg, 1996; Weyant, 1997). Apparently, the conclusion is that it is better to postpone substantial emission reduction for at least a decade.

WRE give four reasons why later abatement may be cheaper: (*i*) the slow turnover time of the power generating capital stock, making drastic emission reduction expensive in earlier decades, as capital is prematurely retired; (*ii*) technological progress, making alternatives to fossil fuel use cheaper in the future; (*iii*) time discounting, diminishing future abatement costs; and (*iv*) the carbon cycle, leaving earlier emissions more time for removal from the atmosphere. The first two reasons imply that `no abatement now' does not mean `no action now': Preparations to move away from a carbon-intensive economy need to be made and, to that end, energy technologies, particularly cheap alternatives to fossil fuels, need to be stimulated.

Arguments against the main conclusion of WRE also count four: (*i*) postponing abatement would lead to a further lock-in to energy and carbon-intensive production and consumption (Grubb, 1997; Ha Duong *et al.*, 1996); (*ii*) technological development is endogenous, and best stimulated by emission abatement (Goulder, 1996; Grubb, 1997; Gruebler and Messner, 1996; Ha Duong *et al.*, 1996); (*iii*) the vast uncertainties in climate change call for a cautious policy (Grubb, 1997; Ha Duong *et al.*, 1996); and (*iv*) postponement of abatement imply likely higher impact of climate change (Alcamo and Kreileman, 1996; Tol, 1997).

This note sheds a different light on the issue. A cost-effective path towards concentration stabilization tacitly assumes a long-lived decision maker with substantial foresight, who is able to plan and prepare for a transition away from carbon emissions for tens of years, and is able to succesfully implement it afterwards. This note seeks insight into the question whether the assumption of a single, long-lived decision maker is crucial for the results obtained by WRE. The answer is that it is, and that releasing it leads to higher near-term abatement.

The next section present a simple but general framework to analyze cost-effective emission reduction targets for alternatives ways to look at technological development. Section 3 discusses the intergenerational implications of cost-effectiveness. Section 4 looks into alternative rules to allocate the emission reduction burden over generations. Section 5 numerically illustrates the qualitative discussion of the earlier sections. Section 6 concludes.

2. A cost-effective emission trajectory

The basic problem of a cost-effective path to a certain concentration stabilization target can be analyzed in the following setting:

$$\begin{aligned} &\min_{R,D} \sum_{t=0}^{T} f_t(R_t, D_t, R_{t-1}, D_{t-1}, \ldots, R_0, D_0) Y_t (1+\delta)^{-t} \\ &\text{s.t.} \quad \sum_{t=0}^{T} (1-R_t) W_t E_t \le M \end{aligned} \tag{1}$$

where E_t denotes unconstrained (business-as-usual) carbon emissions at time t, t=0, 1, ... , T; R_t denotes emission reduction; actual carbon emissions in year t then equal $(1-R_t)E_t$; the constraint on accumulated emissions is M; the weights W_t derive from the carbon cycle, $0 \le W_t \le 1$; Y_t is income; δ denotes the discount rate; D_t are the investments in energy technology research, development and demonstration. D_t and R_t can be controlled by the decision-maker, the other variables are exogenous.

But for the externalities of climate change, business-as-usual emissions and income are assumed optimal. Emission reduction and RD&D are thus costly, and ever more rapidly increasingly so:

$$f_t > 0 \;\; \forall R_t, D_t \neq 0, \quad \frac{\partial f_t}{\partial R_t} > 0, \; \frac{\partial f_t}{\partial D_t} > 0, \quad \frac{\partial^2 f_t}{\partial R_t^2} > 0, \; \frac{\partial^2 f_t}{\partial D_t^2} > 0 \tag{2}$$

RD&D in year t lowers the costs of emission reduction in the years thereafter and, through learning-by-doing, emission reduction has the same effect:

$$\frac{\partial f_{t+s}}{\partial R_t} < 0, \; \frac{\partial f_{t+s}}{\partial D_t} < 0, \; s > 0 \tag{3}$$

Although not explicitly represented with a vintage model of the capital stock, a rapid transition away from the baseline is costly. Note that the effect of learning-by-doing may be offset by early emission reduction consuming cheap alternatives to fossil fuel burning (i.e., if the economic stock of alternatives to fossil fuel is limited in the short-run). The costs of RD&D are ever more rapidly increasing in RD&D; this reflects things such as decreasing returns-to-scale in research and the crowding-out effect described by Goulder and Schneider (1997).

Let us consider the first order conditions. L denotes the LaGrange function, λ the LaGrange multiplier of the constraint on accumulated emissions. Firstly, RD&D in the final year:

$$\frac{\partial L}{\partial D_T} = \frac{\partial f_T}{\partial D_T} \frac{Y_T}{(1+\delta)^T} = 0 \tag{4}$$

so that $D_T = 0$. Investments in RD&D have no benefits (as these would fall beyond time horizon T) but do have costs. Consequently, they are set to zero. In the year before:

$$\frac{\partial L}{\partial D_{T-1}} = \frac{\partial f_{T-1}}{\partial D_{T-1}} \frac{Y_{T-1}}{(1+\delta)^{T-1}} + \frac{\partial f_T}{\partial D_{T-1}} \frac{Y_T}{(1+\delta)^T} = 0 \tag{5}$$

leading to:

$$\frac{\partial f_{T-1}}{\partial D_{T-1}} = -\frac{\partial f_T}{\partial D_{T-1}} \frac{1}{1+\delta} \frac{Y_T}{Y_{T-1}} \tag{6}$$

so that $D_{T-1} > 0$. Similarly,

$$\frac{\partial f_{T-2}}{\partial D_{t-2}} = -\frac{\partial f_{T-1}}{\partial D_{T-2}} \frac{1}{1+\delta} \frac{Y_{T-1}}{Y_{T-2}} - \frac{\partial f_T}{\partial D_{T-2}} \frac{1}{(1+\delta)^2} \frac{Y_T}{Y_{T-2}} \tag{7}$$

and so on for earlier RD&D. Earlier RD&D has larger benefits than later RD&D, so, to a first approximation, (the marginal costs of) investments in RD&D decline over time. This follows from the assumption of a finite time horizon. A discount rate greater than the economic growth rate would also suffice. It is to be noted, however, that the partial derivatives in (6) and (7) are not constant; they change exogenously with time, but also with RD&D and emission reduction. Therefore, no unambiguous conclusion can be drawn with regard to the optimal profile of investment of RD&D; it may decreasing or increasing over time, and need not be monotonic over any period of time.

The case of emission reduction is slightly less complicated, provided that learning-by-doing is not taken into consideration. For the last period,

$$\frac{\partial L}{\partial R_T} = \frac{\partial f_T}{\partial R_T}\frac{Y_T}{(1+\delta)^T} - \lambda W_T E_T = 0 \tag{8}$$

where λ is the Lagrange multiplier for the accumulated emissions constraint. The decision about the last period's emission reduction is thus primarily determined by the necessity to meet the target. Ignoring learning-by-doing for the moment, the first order conditions for all periods' emission reduction have the same form as (8). Then:

$$\frac{\partial f_{t+1}/\partial R_{t+1}}{\partial f_t/\partial R_t} = \frac{W_{t+1}E_{t+1}Y_t(1+\delta)}{W_t E_t Y_{t+1}} \tag{9}$$

so, if the discount rate exceeds economic growth and emissions increase over time, the marginal costs of emission reduction in year t+1 are larger than in year t. If it is as expensive in year t+1 to reduce emissions as in year t, emission reduction in year t+1 is greater than in year t; technological progress would further enhance this. Emission reduction is thus increasing over time. In the first year,

$$\frac{\partial L}{\partial R_0} = \frac{\partial f_0}{\partial R_0}Y_0 - \lambda W_0 E_0 = 0 \tag{10}$$

so that emission reduction exceeds zero if the emission constraint bites and the weight W_0 is positive (in the Maier-Reimer and Hasselmann representation of the carbon cycle, about 15% of emitted carbon dioxide remains forever in the atmosphere; $W_t > 0.15$).

The story gets more involved if learning-by-doing is considered. For the period before last, the first-order condition is

$$\frac{\partial L}{\partial R_{T-1}} = \frac{\partial f_{T-1}}{\partial R_{T-1}}\frac{Y_{T-1}}{(1+\delta)^{T-1}} + \frac{\partial f_T}{\partial R_{T-1}}\frac{Y_T}{(1+\delta)^T} - \lambda W_{T-1}E_{T-1} = 0 \tag{11}$$

so that early emission reduction gets an additional bonus in later years. Similar to the case of RD&D, this bonus is greater the earlier the reduction. This suggests that the emission reduction profile should increase less steeply than in the case without learning-by-doing. However, learning-by-doing lowers emission reduction costs in later years, so that its countervailing effect is at least partly off-set.

The above analysis suggests that the conclusion of WRE, that it is better to postpone drastic emission reduction in favour of RD&D, is apparently robust, at least in a qualitative sense. One may argue about numbers or functional forms, but this paper does not. One may also argue about the assumption of perfect foresight (which allows one to plan and prepare stricter emission controls in the future), and of a single, central decision maker (which allows one to neatly separate emission reduction and RD&D). Instead, this paper looks into the assumption of a single decision maker in time.

3. Intergenerational distribution of costs

Let us consider the intergenerational distribution of the costs of emission reduction. The calculus above also shows that not only the action, but also the costs are shifted to the future. This follows from the increase in marginal reduction costs and the fall of reduction costs because of technological progress. This is partly compensated by the expenditures on RD&D, which would fall with its marginal costs over time (in most cases). It is clear from (1) that generations are not treated at par, and that costs to future generations matter less than do costs to the present generation. Therefore, there is an in-built tendency to shift the costs of emission abatement to future generations of decision makers.

It is this result that would concern a future decision maker. However, under the assumptions above, if the decision maker in year *0* acts optimally, then a recomputation of the cost-effective path in year *1* would lead the then decision maker to act optimally as if the calculus was done in year *0* -- and so on. This is because the first-order conditions for the cost-effective decision in year *1* only differ from those for year *0* by a factor $(1+\delta)$, which drops out the equations, and by the action in year *0*, which is equal by assumption.

The situation changes if the decision maker in year *1* were allowed to re-evaluate the concentration target as well. Supposedly, the target *M* was set by the decision maker in year *0* as a perceived balance between the costs of emission reduction and the impacts of climate change. Following the cost-effective path, the costs of emission reduction would have gone up in year *1*, but the impacts of climate change have changed little.[1] The cost-effective path designed in year *0* thus creates incentives for decision-makers in years *1* and beyond to soften target *M*.

The cost-effective path is a potential Pareto improvement. The standard way to make a potential into an actual Pareto improvement is to let the winners compensate the losers. Provided that utility is transferable (it is money in this case), such compensation is always possible. In this case, the earlier generations benefit, so they should compensate later generations. This is easier than the other way around, but not without problems. Although the decision-maker in year *0* could set aside funds to compensate later decision-makers, there is nothing to prevent them from

---

[1] The marginal impacts even may have gone down, that is, if the current best guess of impacts being approximately quadratic in natural logarithm of the stock of atmospheric carbon is correct.

accepting the compensation and softening the target anyway.[2] It is also doubtful whether the current decision maker would want to set aside funds. For, this would increase current costs considerably, giving the current decision maker also a reason to soften target *M*. This is the core of the problem: the constraint on accumulated emissions is a political choice by one generation; it is not necessarily a rational choice for each generation (and perhaps for none). In the next section, I try to reconcile the collective (semi-)rationality of intertemporal cost-effectiveness with individual rationality of each generation of decision makers.

4. Alternatives

As a first step, one could alter the discount rate, the prime instrument of intergenerational allocation. The effect can easily be seen from the first order conditions treated above. If the discount rate just equals economic growth (with welfare linear in money, this implies a zero rate of pure time preference), the marginal costs and benefits of RD&D are, at a first approximation, equalized; see (6) and (7). Ignoring learning-by-doing, the marginal costs of emission reduction are equalized, corrected for the emissions' share in the constraint on accumulated emissions; see (9). The marginal cost profile of RD&D declines more steeply in this case, leading to more RD&D in the earlier period. The marginal cost profile of emission reduction becomes less steep. Combined with the lower reduction costs in the future (because of earlier RD&D) and the constraint on accumulated emissions, emission reductions in earlier years go up. The learning-by-doing effect works in the same direction. The effect is unambiguous and unsurprising: the lower the discount rate, the higher current action.

Tinkering with the discount rate still leaves one in the realm of cost-effectiveness analysis, founded on the basic notion of economic efficiency. As noted above, the target for cumulative decisions need not be based on considerations of economic efficiency. Indeed, in a full-blown cost-benefit analysis, each generation of decision makers would equate its marginal emission reduction costs with its marginal benefits of avoided climate change. The whole issue of compliance to an efficient path would be redundant, as each generation would face the right (i.e., its own) incentives.

A solution to the intergenerational distribution of emission targets may be the concept of non-envy, which would take one further away from issues of efficiency, but closer to a basic notion of equity, namely an equal distribution of abatement costs (relative to income). This could be the result of a negotiation with all generations together at one time in one room.[3] In this case, emission reduction hurts every generation, but it is obvious to all decision makers involved that one generation's pain is not higher than any other generation's pain. The effect of a non-envy solution is clear. Firstly, the effect that earlier emissions count less in the constraint on

---

[2] Note that the stock of knowledge generated by current RD&D leaves an inheritance more designated to emission reduction (as it is cheaper) while the knowledge stock cannot be exclusively used for other purposes.

[3] a counterfactual situation not unlike Rawls' (1972) veil of ignorance

accumulated emissions is abandoned. This leads to higher reduction in the near term. Secondly, total rather than marginal costs are equated. This leads to higher reduction in the years with expensive, steep cost functions, and less reduction in the years with cheap, flat cost functions. A non-envy solution implies higher reduction in the earlier decades, because it forbids that advantage is taken of less expensive abatement in later decades. It is to be noted that under technological progress, be it exogenous or endogenous, cost equalization still leads to an upward sloping emission reduction profile. Note also that, at least in the MERGE model (Manne and Richels, 1997a), neither the WRE path nor the WGI path to a 550 stabilization is a non-envy solution; in the former, future generations bear a disproportional cost, in the latter, the current generation does.

5. A numerical illustration

Some numerical examples further illustrate the issues. Income is 100 in year 0, increasing with 20% per decade. The discount rate is 20% or 30% per decade. Emissions are 100 in year 0, increasing with 10% per decade. Emission reduction costs $\alpha_t R_t^2$, where $\alpha_t = \alpha_{t-1}\exp(-\gamma_R R_{t-1} - \gamma_D D_{t-1})/(1+\tau)$. $\tau = 0.1$ per decade. The γs are either 0 or 1, denoting absence and presence of learning-by-doing and purchased RD&D. RD&D costs βD_t^2. The weights of the carbon emissions are $W_t = 0.16 + 0.04t$. The number of periods is 20. Unconstrained emissions accumulate to 4500. The emission constraint is put at two-thirds of this: 3000.

Figure 1 shows cost-effective emission trajectories with and without RD&D (R) and learning-by-doing (L), in case the discount rate exceeds economic growth (positive pure rate of time preference). Earlier emission reductions are lower than later abatement. RD&D steepens the curve. Learning-by-doing leads to more abatement up-front; if γ_R is made sufficiently high, learning-by-doint leads to less abatement up-front.

Figure 2 displays the associated relative costs. These slope upwards, at different rates. However, the cases are not readily comparable, as RD&D and learning-by-doing add options without a recalibration of the baseline.

Figure 3 repeats Figure 1 with a zero pure time preference. Abatement starts earlier, and rises less steeply. Figure 4 presents the associated relative costs. Early expenditure is higher than in the case of a positive time preference, but the high costs of the later decades (not shown in Figure 2) are moved forward.

Figure 5 displays the investment in RD&D. With a positive time preference, the investments slope upwards (i.e., RD&D expenditures are shifted to the intermediate generations, who pave the way for steep emission reduction by the later generations). With a zero time preference, RD&D gently slopes downward. Learning-by-doing does not alter the pattern, but obviously does affect the level of RD&D.

Figure 6 summarizes the findings with the cost-effective emission reduction in the first period. Reduction is nowhere zero. Reduction is higher with learning-by-doing and a low discount rate, and higher with purchased RD&D.

Figure 7 gives emission reduction for a non-envy solution in which relative costs are equalized across generations. In the absence of RD&D, emission reductions are fully determined by this constraint and the one of accumulated emissions. In case RD&D is included, it is optimized using a zero time preference. Emission reduction is still upward sloping, but earlier reductions are higher. With RD&D and without learning-by-doing, it makes still a lot of sense to invest heavily in research and do little on abatement. Figure 8 further illustrates this.

Figure 9 finally summarizes the numerical experiments for the first decade. A low discount rate and a non-envy solution increase the extent of early action. So does learning-by-doing. RD&D reduces early abatement.

6. Conclusion

To a first approximation, postponing emission abatement is cost-effective. However, the actual emission profile is highly sensitive to disputable assumption about technological development. More seriously, cost-effectiveness may not be an appropriate way to look at the distribution emission reduction over generations. By its definition, a cost-effective abatement trajectory adheres to the collective rationality of all relevant generations. A positive rate of pure time preference implies that generations are not treated at par, implying that cost-effectiveness does not adhere to principles of intergenerational equity nor to the rationality of later generations. Cost-effectiveness also tacitly assumes that capital transfers are possible to reallocate the economic consequences of the different abatement efforts. This assumption is false in an intergenerational context. A non-envy emission trajectory is put forward as an alternative, still allowing for intergenerational differences in action but not for cost differences. This is likely to lead to higher expenditures on emission reduction and RD&D in the earlier decades, or to softer targets for accumulated emissions. In any case, RD&D deserves a prominent place in today's portfolio.

References

Alcamo, J. and Kreileman, E. (1996), *Interim Environmental Impacts of Delaying Emission Controls (preliminary results)* (draft).

Edmonds, J.A., Dooley, J. and Wise, M. (1997), `The Role of Energy Technology in Atmospheric Stabilization', in Flannery, B.P., Kohlhase, K.R. and LeVine, D.G. (eds.) *Critical Issues in the Economics of Climate Change*, IPIECA, London.

Goulder, L.H. (1996), *Notes on the Implications of Induced Technological Change for the Costs and Benefits of Carbon Abatement* (draft).

Goulder, L.H. and Schneider, S.H. (1997), *Induced Technological Change, Crowding Out, and the Attractiveness of CO_2 Emissions Abatement* (draft).

Grubb, M.J. (1997), `Technologies, Energy Systems and the Timing of CO_2 Emissions Abatement', *Energy Policy*, **25** (2), 159-172.

Gruebler, A. and Messner, S. (1996), *Technological Change and the Timing of Abatement Measures* (draft).

Ha Duong, M., Grubb, M.J. and Hourcade, J.C. (1996), *Optimal Emission Paths Towards CO_2 Stabilisation and the Cost of Deferring Abatement: The Influence of Inertia and Uncertainty* (draft).

Manne, A.S. and Richels, R.G. (1997a), *On Stabilizing CO_2 Concentrations: Cost-Effective Emission Reduction Strategies* (draft).

Manne, A.S. and Richels, R.G. (1997b), `The Greenhouse Debate -- Economic Efficiency, Burden Sharing and Hedging Strategies', in Flannery, B.P., Kohlhase, K.R. and LeVine, D.G. (eds.) *Critical Issues in the Economics of Climate Change*, IPIECA, London.

Peck, S.C. and Teisberg, T.J. (1996), `International CO_2 Emissions Targets and Timetables: An Analysis of the AOSIS Proposal', *Environmental Modeling and Assessment*, **1** (4), 219-227.

Rawls, J. (1972), *A Theory of Justice*, Cambridge University Press, Cambridge.

Tol, R.S.J. (1997), `On the Difference in Impact between Two Almost Identical Climate Scenarios', *Energy Policy* (forthcoming).

Weyant, J.P. (1997), `Insights from Integrated Assessment', in Flannery, B.P., Kohlhase, K.R. and LeVine, D.G. (eds.) *Critical Issues in the Economics of Climate Change*, IPIECA, London.

Wigley, T.M.L., Richels, R.G. and Edmonds, J.A. (1996), `Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations', *Nature*, **379**, 240-243.

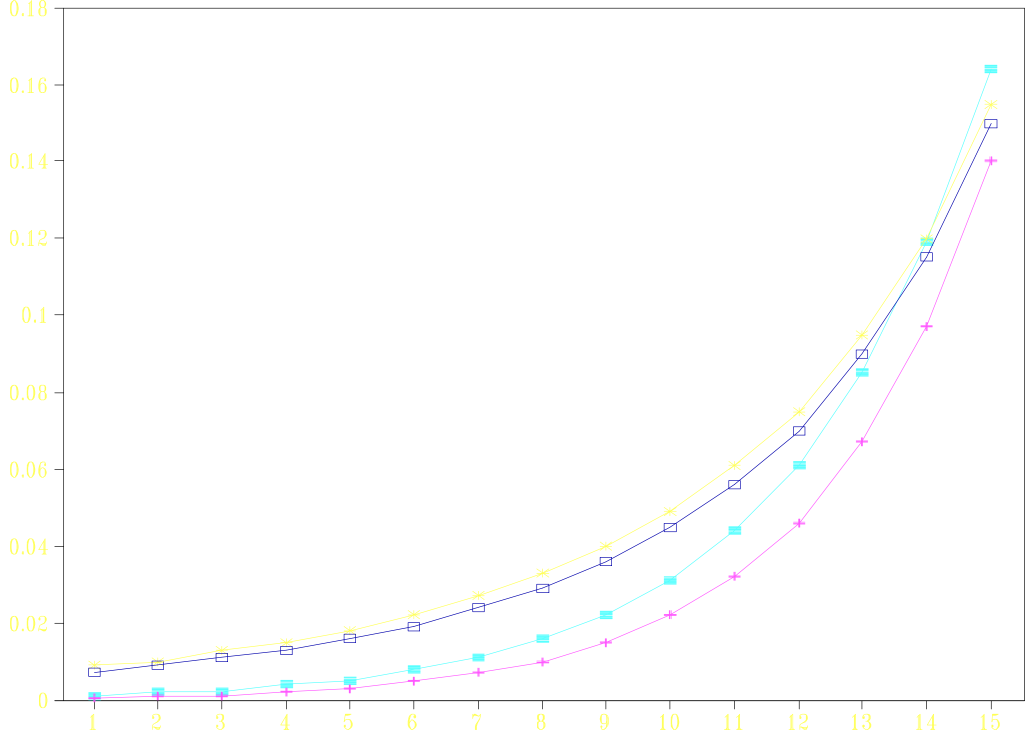

Figure 1. Emission reduction (as share of uncontrolled emissions) for periods 1-15 without RD&D and learning-by-doing (filled squares), with RD&D (plusses), with learning-by-doing (asterisks), and with RD&D and learning-by-doing (empty squares) for a discount rate exceeding the economic growth rate.

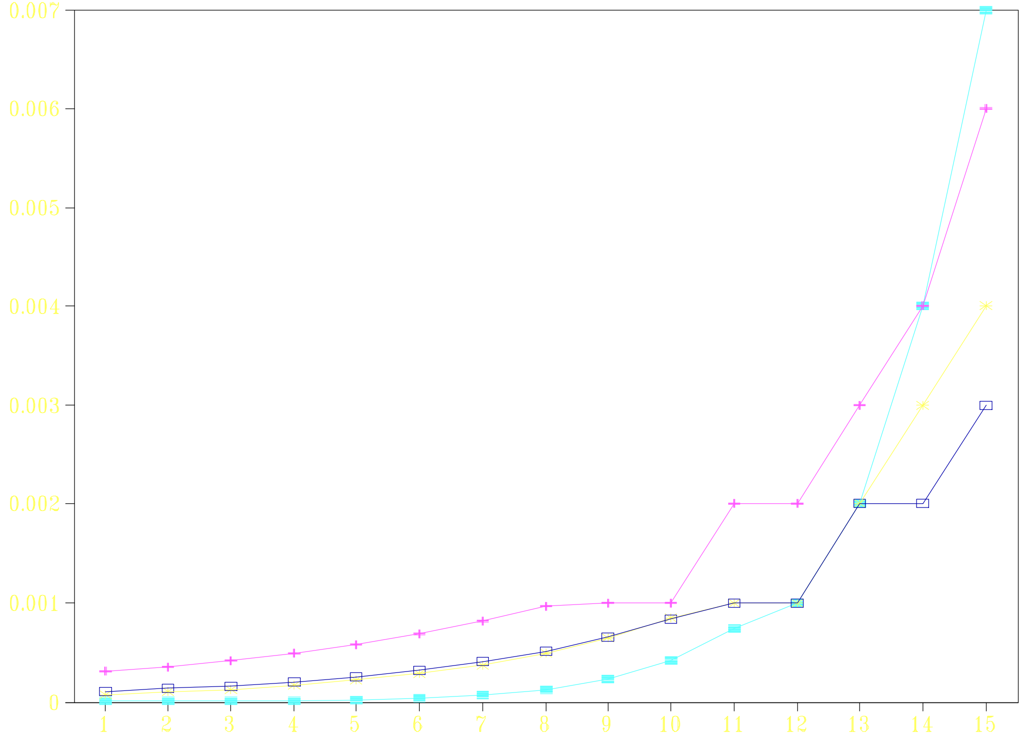

Figure 2. Cost of emission reduction (as share of economic output) for periods 1-15 without RD&D and learning-by-doing (filled squares), with RD&D (plusses), with learning-by-doing (asterisks), and with RD&D and learning-by-doing (empty squares) for a discount rate exceeding the economic growth rate.

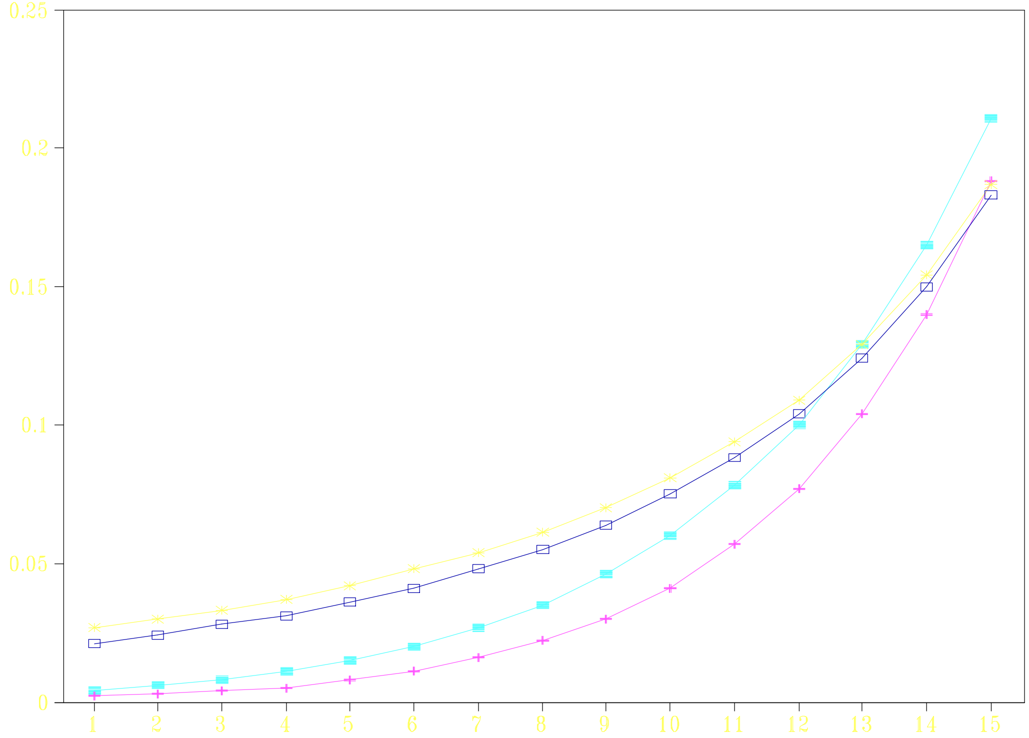

Figure 3. Emission reduction (as share of uncontrolled emissions) for periods 1-15 without RD&D and learning-by-doing (filled squares), with RD&D (plusses), with learning-by-doing (asterisks), and with RD&D and learning-by-doing (empty squares) for a discount rate equal to the economic growth rate.

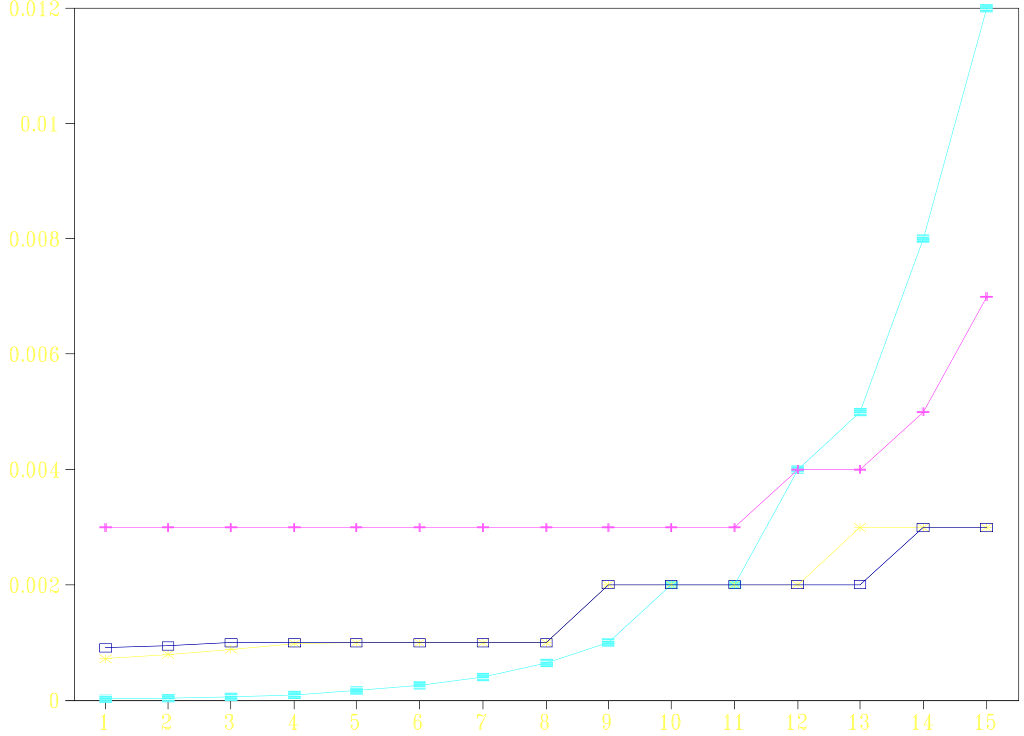

Figure 4. Cost of emission reduction (as share of economic output) for periods 1-15 without RD&D and learning-by-doing (filled squares), with RD&D (plusses), with learning-by-doing (asterisks), and with RD&D and learning-by-doing (empty squares) for a discount rate equal to the economic growth rate.

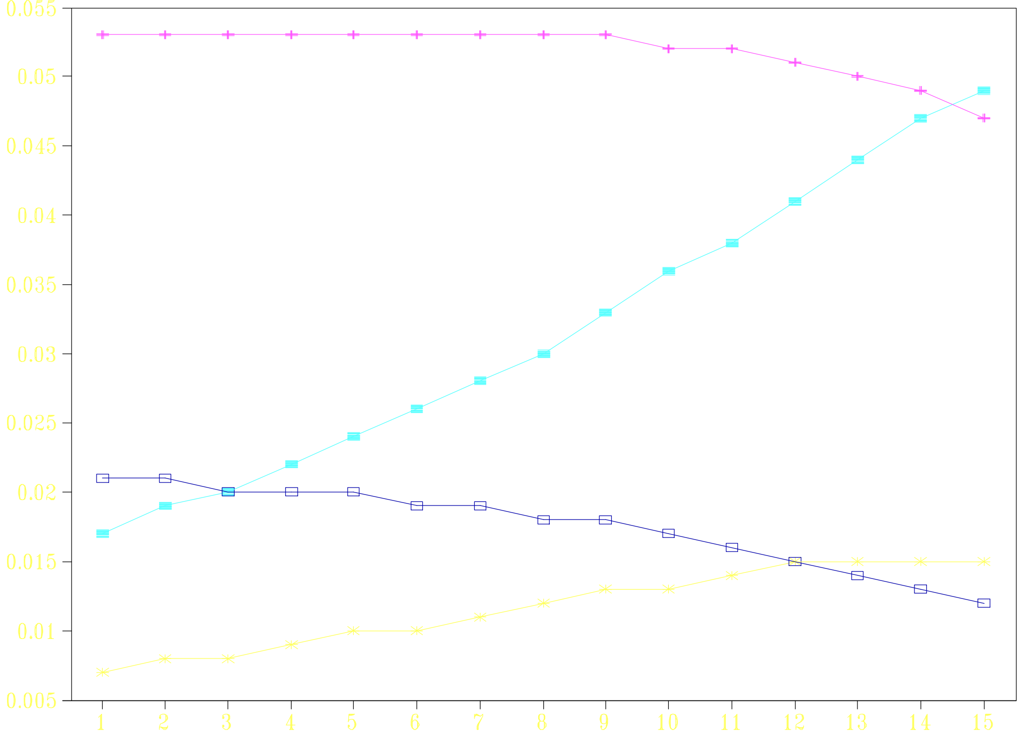

Figure 5. Investments in research, development and demonstration for periods 1-15 for a discount rate equal to the economic growth rate (plusses and empty squares) or exceeding it (asterisks and filled squares), and with learning-by-doing (asterisks and empty squares) or without (plusses and filled squares).

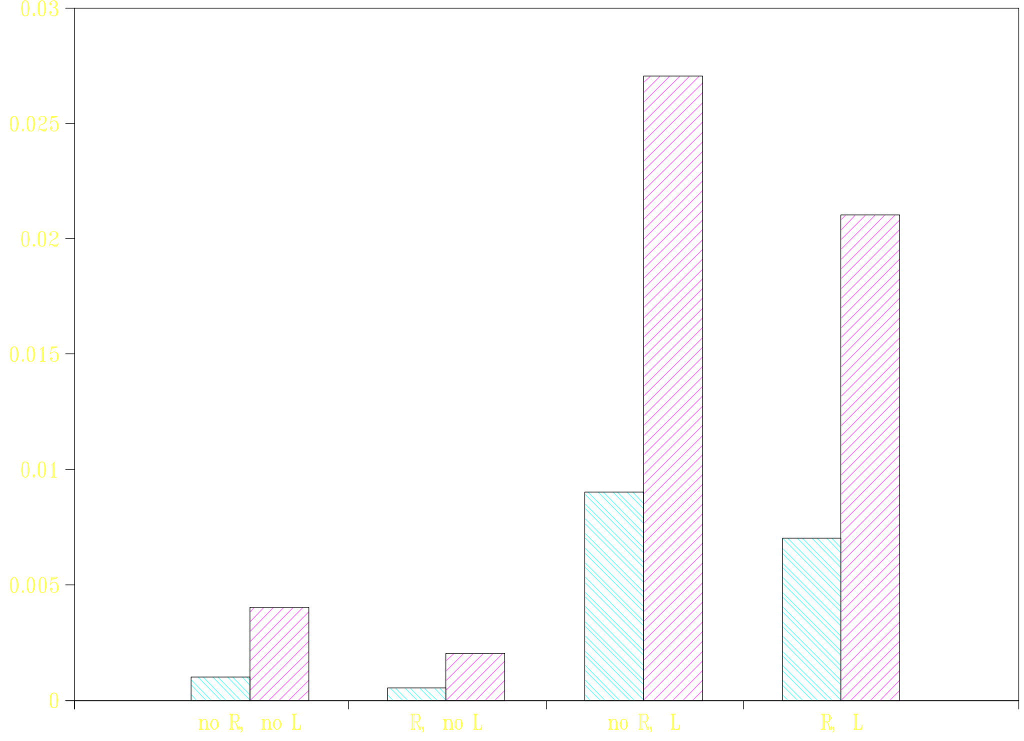

Figure 6. Emission reduction (as share of uncontrolled emissions) for period 1 with and without RD&D (R) and learning-by-doing (L) for a discount rate equal to the economic growth rate (///) and exceeding it (\\\).

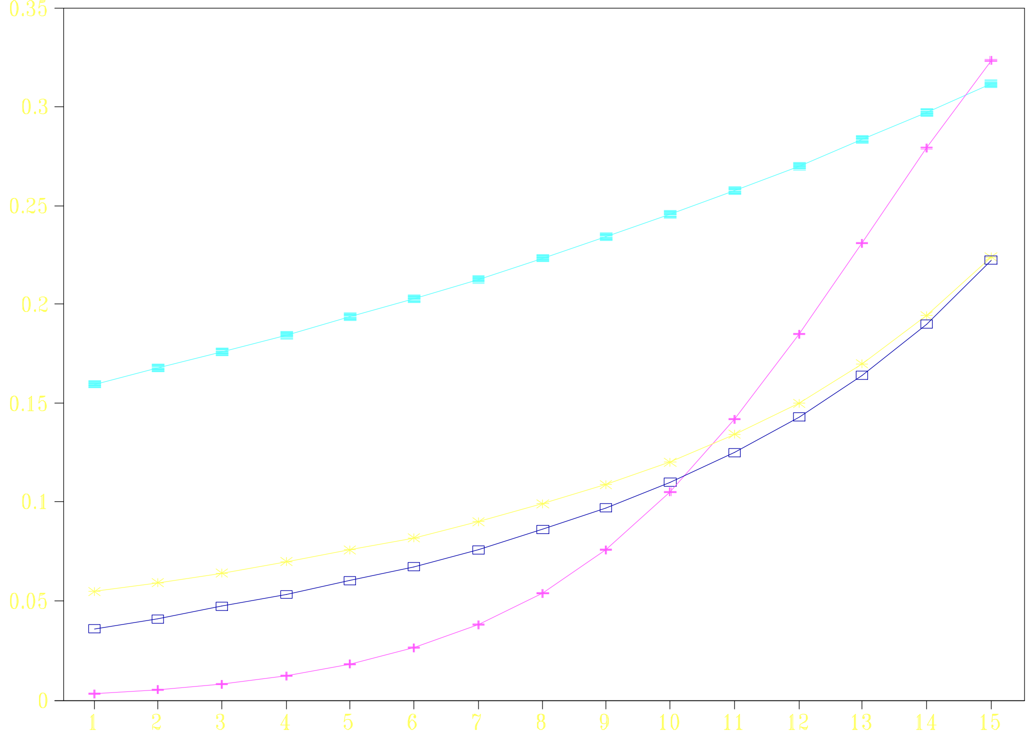

Figure 7. Emission reduction (as share of uncontrolled emissions) for periods 1-15 without RD&D and learning-by-doing (filled squares), with RD&D (plusses), with learning-by-doing (asterisks), and with RD&D and learning-by-doing (empty squares) for a non-envy solution (i.e., relative costs equal for all periods).

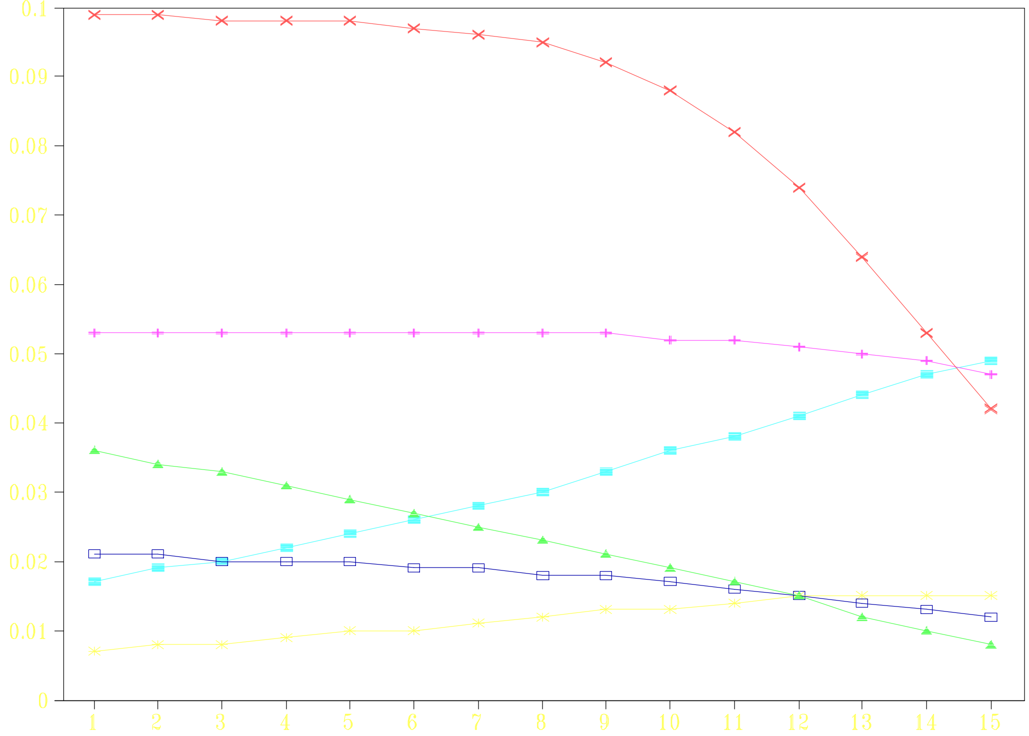

Figure 8. Investments in research, development and demonstration for periods 1-15 for a discount rate equal to the economic growth rate (plusses and empty squares) or exceeding it (asterisks and filled squares), or a non-envy solution (crosses and triangles), and with learning-by-doing (asterisks, empty squares and triangles) or without (plusses, crosses and filled squares).

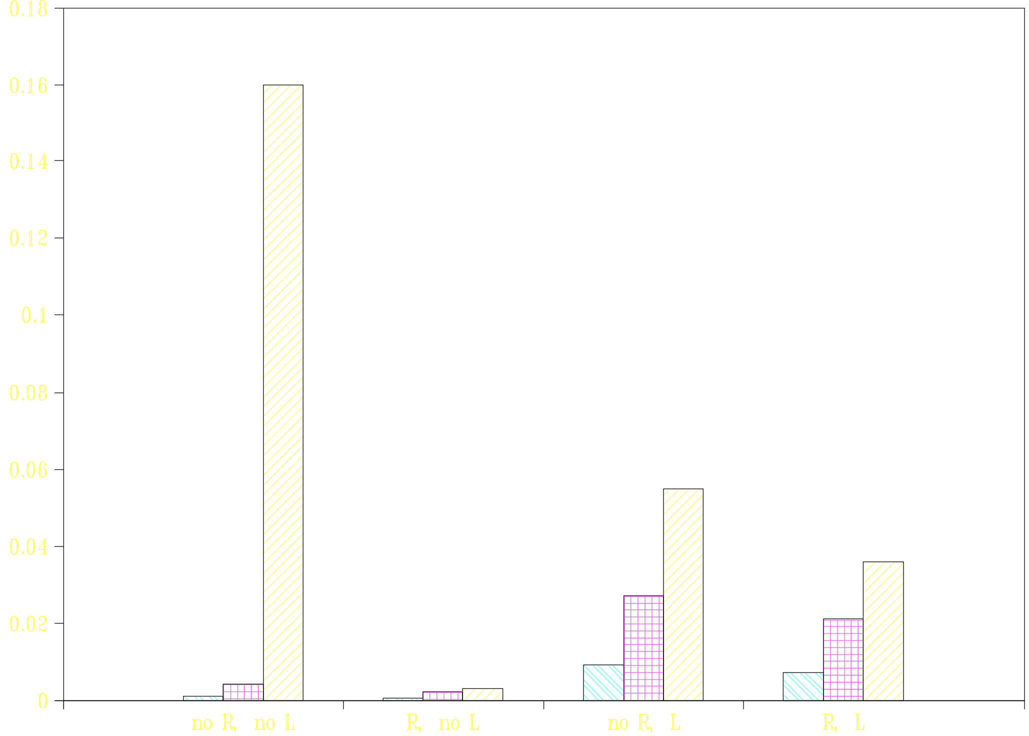

Figure 9. Emission reduction (as share of uncontrolled emissions) for period 1 with and without RD&D (R) and learning-by-doing (L) for a discount rate equal to the economic growth rate (+++), exceeding it (\\\) and a non-envy solution (///).